SUI-63-13

# LATITUDE SURVEY OF COSMIC RAY INTENSITY BY EXPLORER VII, OCTOBER 1959 TO FEBRUARY 1961*

by

W. C. Lin, D. Venkatesan,
and J. A. Van Allen
Department of Physics and Astronomy
State University of Iowa, Iowa City, Iowa

April 1963

*Supported in part by the Office of Naval Research Contract N9onr 93803 and by the National Aeronautics and Space Administration Grant NsG-233-62.



NASA CR-50,419

## ABSTRACT

18167

Using a shielded Geiger tube in the Explorer VII satellite there has been conducted a comprehensive geographic survey of the intensity of charged particles in the latitude range $\pm 50.5°$, in the altitude range 550 to 1100 km, and over the sixteen month time period October 13, 1959 to February 17, 1961. It has been found possible to identify and eliminate contributions by geomagnetically trapped particles and thus to obtain the absolute intensity of primary galactic cosmic rays and their charged particle secondaries (albedo) produced in the atmosphere. Specific results are as follows:

(a) The counting rate data from both Northern and Southern Hemispheres and over a considerable range of longitudes are represented in a simple and coherent manner as a function of a single parameter, the McIlwain magnetic shell parameter L.

(b) The counting rate increases monotonically with increasing L and has an accurately constant value for $L > 2.9$.

(c) The high latitude knee of the counting rate vs L curve occurs at $L = 2.6$ (corresponding to the invariant latitude 52°) and is indiscernibly different in the Northern and Southern Hemispheres.

(d) The absolute omnidirectional intensity is $0.56\ (\text{cm}^2\ \text{sec})^{-1}$ at the equator and $2.0\ (\text{cm}^2\ \text{sec})^{-1}$ at high latitudes, the ratio being 3.6.

(e) At high latitudes, the intensity increases by the factor $1.046 \pm 0.045$ during the sixteen month period.

(f) In terms of the Quenby-Wenk vertical cut-off rigidity R in BV, the total omnidirectional intensity $J_o (> R) = 4.3\ R^{-0.83 \pm 0.02}\ (\text{cm}^2\ \text{sec})^{-1}$ for $3 < R < 12$ BV and $J_o = 2.0\ (\text{cm}^2\ \text{sec})^{-1}$ for $R < 1.7$ BV.

## INTRODUCTION

The extensive data from the shielded 112 Geiger tube on Explorer VII over a period of seventeen months have been used to study the latitude dependence of cosmic ray intensity in a much more comprehensive way than has been possible heretofore. Moreover, the observations have been made above the appreciable atmosphere, in both Northern and Southern Hemispheres and over a wide range of longitudes. The present study uses about 5000 data points from over 2000 passes.

The earliest systematic surveys of cosmic ray intensity over the surface of the earth were made by Millikan and Neher [Millikan, 1933; Millikan and Neher, 1936] and by Compton [1933]. The latter author noted that loci of constant intensities correlated better with geomagnetic latitude than with geographic. The inadequacy of the geomagnetic coordinate system derived from the dipole approximation of the geomagnetic field, for a study of the observed spatial distribution of cosmic ray intensities was pointed out by Simpson et al. [1956], Rose et al. [1956], and Rothwell and Quenby [1958].

Quenby and Webber [1959] devised a new, approximate method for estimating vertical cut-off rigidities giving special attention to the configuration of the real geomagnetic field in the vicinity of the point at which the value of the cut-off is desired. The Quenby-Webber locus of points having a maximum value of cut-off at specified longitudes was in substantial agreement with the observed locus of points at which minimum values of cosmic ray intensities were observed (the observed "cosmic ray equator").

Lin and Van Allen [1963] attempted to use the Quenby-Webber cut-offs at high latitudes to organize a large body of Explorer VII data on the positional dependence of the intensities of solar cosmic rays. It was found that the loci of constant intensity of arriving solar cosmic rays were in marked disagreement with loci of constant Quenby-Webber cut-offs. However, all of the Explorer VII data in both hemispheres and at various longitudes were organized in a coherent manner when plotted against the magnetic shell parameter L [McIlwain, 1961]. Clear theoretical foundations underlie the definition of the L parameter as a "good coordinate" for the description of the intensities of charged particles which are <u>trapped</u> in the geomagnetic field, at least up to $L \sim 5$. But initially, the empirical success of the L parameter in organizing observations of the intensities of charged particles arriving from infinity was understood only on the semi-intuitive grounds that particles whose magnetic rigidities are just above the cut-off value, for a specified site, approach the earth in the Alfvén manner along a line of force. The locus of a family of equivalent lines of force is approximately a shell of constant L. Recent studies by Sauer [1963], Ray and Sauer [1963], and Ray [1963] have provided an approximate basis of an essentially rigorous theoretical nature for the use of the L parameter as a "good coordinate" for describing the arrival of charged particles from infinity.

Meanwhile, improved sets of vertical cut-off rigidities for the geomagnetic field have been computed by Quenby and Wenk [1962] and by a new and quite different method by Sauer [1963]. A summary comparison of the results of the several methods of computing cut-off is given by the latter author.

In the present paper, McIlwain's L, computed at the geographic latitude, longitude, and altitude of each observed datum, has been used as the basic "magnetic latitude" parameter.

The orbital characteristics of Explorer VII are given below: Perigee altitude--about 550 km; apogee altitude--about 1100 km; inclination--50.5°; anomalistic period--101 minutes. The apparatus consisted of two radiation detectors, a small unshielded Anton 302 Geiger tube, and a larger, shielded Anton 112 Geiger tube. The scaling factors for the counters were respectively 2048 and 128.

The 112 counting rates have been utilized for systematic studies of solar proton events [Van Allen and Lin, 1960; Lin and Van Allen, 1963] and the 302 counting rates for the time variations of the inner and outer radiation zones [Forbush, Venkatesan, and McIlwain, 1961; Pizzella, McIlwain, and Van Allen, 1962; Forbush, Pizzella, and Venkatesan, 1962].

In the present study counting rates of the 112 tube have been adopted as primary data. Data from the 302 tube have been used only for the auxiliary purposes of assessing the contribution of trapped particles to the rate of the 112; of correcting the rate of the 112 when the appropriate correction was small and could be made reliably; and of discarding 112 data when the correction was too large to be made reliably.

The detection thresholds for the 112 tube [Van Allen and Lin, 1960; Ludwig and Whelpley, 1960] are 30 MeV for protons, 2.5 MeV for electrons, and 80 keV for x rays (5% transmission). The absorbers covering over 70% of solid angle consist of 0.040 $gm/cm^2$ stainless steel, 0.26 $gm/cm^2$ of Al, 1.15 $g/cm^2$ of Pb, and 0.14 $g/cm^2$ of Mg. The geometric factor is 7.2 $cm^2$; hence omnidirectional intensity is obtained by dividing the counting rate by 7.2.

The shielding of the 112 tube removes much of the trapped radiation. This fact as well as the small scaling factor enables the convenient study of the spatial distribution of cosmic ray intensity. Most of the data correspond to cases where the satellite was outside the belts of trapped radiation; or where reliable correction could be made for the residuum of trapped particles in the manner described by Van Allen and Lin /1960/. (Note, however, the exceptions to this statement in the discussion accompanying Figure 3.)

Data from the following receiving stations have been used: Woomera, Australia; Hawaii; San Diego; Iowa City; and Blossom Point. Whenever overlapping of data occurs, duplicate data have been rejected. Plots of raw counting rate versus time for each pass are examined first. From these plots, one can observe clearly a sharp rise in counting rate whenever the satellite enters the radiation zone. The selection of data was based on detecting this point and using all data points below it. For the high latitudes, namely $L > 3.0$, there are instances when the outer zone peak has shifted to lower L values /Forbush, Pizzella, and Venkatesan, 1962/, and the counting rates are low (less than 100 counts/sec). In such cases, it is possible to correct adequately for the residuum of the softer radiation. This was done after the procedure of Van Allen and Lin /1960/ and as explained in detail by Lin and Van Allen /1963/, using the simultaneously observed 302 counting rate, and the linear relationship observed between the 112 and 302 counters. The paucity of data for the higher latitudes results from discarding those data which cannot be corrected reliably.

The counting rates have been plotted as a function of L, the magnetic shell parameter. The invariant latitude $\Lambda$, which is defined by $\Lambda = \cos^{-1} L^{-1/2}$ and which has the nature of a "geomagnetic latitude", has also been shown. L is measured in units of earth radii.

Figure 1 gives a plot of L contours at an altitude of 1000 km, for several selected values of L. On the same diagram are shown the regions within which our observations are obtained.

## OBSERVATIONAL RESULTS AND DISCUSSION

In Figure 2, we have plotted the counting rate of the 112 tube, registered over Woomera, Australia, as a function of L. The L values have been computed using the Finch and Leaton [1957] coefficients for the geomagnetic field for the epoch 1955. The study of the Explorer I data on the altitude dependence of trapped particle intensity by Yoshida, Ludwig, and Van Allen [1960] revealed that the lower boundary of the inner radiation zone over the lower latitude region over Australia is at an altitude of about 1480 km, as determined with a similar Geiger tube. Therefore it is clear that at the Explorer VII satellite altitudes of 550 to 1100 km, the observed counting rate is due dominantly to cosmic rays. In the region of higher L values corresponding to higher latitudes, the contribution due to the trapped particles in the outer zone was subtracted as explained earlier. The time taken for a half cycle (64 counts) is used to determine the counting rate for $L \leq 3.0$, and the time taken for a full cycle (128 counts) is used for $L > 3.0$. Data obtained during Forbush type variations were removed by reference to ground level neutron monitor data throughout the period. It is relevant to recall an example, namely that of a Forbush decrease of about 24% observed at $L \gtrsim 4.0$ by

Explorer VII on March 31, 1960 in contrast to about 10% in the neutron monitor data at Deep River [Van Allen and Lin, 1960]. Data observed during solar cosmic ray events were also removed. Except for the event of November 12, 1960, solar cosmic rays were not observed for L $\lesssim$ 2.0. The results of an analysis of the data connected with solar cosmic ray events and Forbush type decreases of galactic cosmic ray intensity is given by Lin and Van Allen [1963].

The statistical standard deviation of each plotted point in Figure 2 is 13% for L $\leq$ 3.0 and 9% for L > 3.0. The majority of the points fall within one standard deviation from a mean line drawn through the points and hence there is no discernible time variation in the data. The figure shows a 3.6 fold increase in counting rate from L = 1.2 to L $\simeq$ 2.6 (the latitude dependent part) and a constant counting rate at higher L values (the latitude independent part).

Figure 3 shows the plot of the data registered over the four Northern Hemisphere stations: Hawaii; San Diego; Iowa City; and Blossom Point. The distribution of most of the points exhibits the same characteristics as do the data from Woomera (Figure 2): viz., an L-dependent (latitude dependent) part up to L $\cong$ 2.6 and a plateau for larger L values. It is of interest to note that the counting rate of a 112 tube in Ranger I on November 18, 1961 at an altitude of 192 km over North America fits well within the cluster of points at L = 1.62 /Frank and Van Allen, 1963/.

But in addition there are a considerable number of points which depart markedly from the main concentration in the range L $\lesssim$ 2.2. The crosses in the graph designate all points in the altitude range 1000-1100 km, for L < 3.0. It is seen that most of the population of wild points are from data in the altitude range 1000-1100 km. Nonetheless there are many points in this altitude range which lie within the main concentration of points in a distribution similar to that of Figure 2.

Yoshida et al. /1960/ observed the lower boundary of the inner radiation belt in 1958 at altitudes as low as 800 km over Ibadan, Nigeria and 1100 to 1200 km over western United States. Hence the wild points in Figure 3 may be attributed plausibly to the intermittent presence of trapped particles at the altitudes of the Explorer VII observations. Since the trapped radiation in the inner belt is much more penetrating than that at L > 2.3, the effect of the differential shielding of the 112 and 302 tubes is insufficient to make it possible to subtract reliably the contribution of trapped radiation to the 112 counting rate by the technique mentioned earlier and applied to data in the lower fringe of the outer radiation belt. The data at $L < 2.6$ in Figure 3 have not been corrected in any way.

The Northern Hemisphere data are spread over the longitude range 170° E to 65° W (cf., Figure 1). Since scalar B on a given magnetic shell ($L = \text{const}$) at a given altitude is a function of longitude it is first necessary to examine the data for longitude dependence. All of the counting rate data in the altitude range 1000 to 1100 km were plotted against longitude for fixed values of L, but no statistically significant dependence on longitude was found.

Hence we conclude that the wild points in Figure 3 are attributable to the intermittent presence of trapped particles at the altitudes of the observations and thus represent a feature of the time variation of the lower fringe of the inner radiation belt (cf., Pizzella, McIlwain, and Van Allen, 1962, and Garmire, 1962). An attempt was made to investigate the association between geomagnetic storms and the occurrence of wild points, but the data were insufficient to establish any definite relationship. In common with previous authors we are unable to propose a detailed mechanism for such time variations but it may be noted (a) that the trapped particle intensity is an extremely steep function of altitude, and (b) that the 112 tube is a sensitive detector of very mild intrusions of the inner zone by virtue of its large geometric factor and low cosmic ray counting rate. (The counting rate of such a tube in the heart of the inner zone would exceed $2 \times 10^5$ counts/sec.)

Well known general possibilities are the following:

(a) Perturbation of mirror points of trapped particles by fluctuations in the geomagnetic field, either adiabatically or non-adiabatically.

(b) Transient heating of the exosphere with accompanying changes of the rate of out-scattering of trapped particles.

(c) Impulsive injection of fresh particles from solar cosmic ray events (either via neutron albedo or by more direct means).

It is clear that Explorer VII observations over Australia are much less subject to mild perturbations in the lower fringe of the inner zone than are those in the Northern Hemisphere since the lower boundary of the inner zone is normally several hundred kilometers higher over Australia.

The results from the Northern and Southern Hemispheres are shown together in Figure 4. All the data from the Southern Hemisphere have been used (Figure 2) and all data from the Northern Hemisphere at altitudes below 1000 km (Figure 3) have been used. In each case the average counting rate of the data within a specified increment of L is plotted at the center of the interval. For $L < 2.8$, a uniform increment $\Delta L = 0.1$ was used. The excellent agreement between the Southern Hemisphere data and the Northern Hemisphere data below 1000 km adds support to the view that the wild points in Figure 3 arise from the occasional presence of the lower fringe of the inner zone over the Northern Hemisphere stations in the 1000-1100 km range.

14

## INTERPRETATIVE REMARKS

The counting rate of the 112 tube is an approximately linear function of L in the range $1.2 \leq L \leq 2.5$. It is accurately independent of L for $L > 2.9$. A straight line through the experimental points in the range $1.2 \leq L \leq 2.5$ (Figure 4) cuts the horizontal line representing the data for $L > 2.9$ at $L = 2.6$. This point is termed the latitude "knee" of the curve and is, of course, the average value for the era October 1959 to February 1961. The corresponding value of invariant latitude is 52°. It is indistinguishably different for Northern and Southern Hemispheres, as is the value of the high latitude counting rate.

On the basis of an extensive series of balloon flights of omnidirectional ionization chambers, Neher [1961] found that in the period June-December 1958

(a) The ionization was very nearly a symmetrical function of centered dipole latitude (except for a small "longitude effect") with the minimum value at the dipole equator [cf., Chapman, 1963];

(b) The dipole latitude of the knee was accurately the same at northern and southern latitudes and increased monotonically with increasing altitude within the atmosphere;

(c) The dipole latitude of the knee at zero atmospheric depth was estimated to be 55°;

(d) The ionization at the maxima of the successive ionization vs atmospheric depth curves increased by a factor of 3.05 from the equator to the knee; and

(e) There was a slight increase in ionization above the knee as one approached 90° latitude.

On the basis of nine rocket flights of single Geiger tubes over a wide range of latitudes (75° N to 71° S geographic latitudes) Van Allen and Cahill [1958] reported as follows:

> "The total intensity above the atmosphere at far southerly latitudes is the same within 5% as that at far northerly latitudes. It is about 4.3 times as great as that near the equator. The latitude knee (during the present period of high solar activity lies at a lower latitude than 50° North or 50° South."

The results of these two earlier surveys are generally concordant with the Explorer VII survey and it is not clear whether the discrepancies should be attributed to differences in technique, to true time variations, or to the use of different coordinate systems. Inasmuch as it is now known that L-derived and Quenby-Wenk cut-off rigidities provide coordinate systems which are superior to the centered dipole one, it would be of interest to see the data of Neher replotted in these systems.

Figure 5, reproduced from a paper by Lin and Van Allen /1963/ shows the relationship between L and the vertical cut-off rigidities /Quenby and Wenk, 1962/. Combining this with Figure 4, we find that the rigidity at $L = 2.6$, corresponding to the observed knee, is 2.2 BV (units of billion volts or $10^9$ volts). Thus by reference to Figure 4 and later discussion it is concluded that the primary cosmic ray spectrum had less than 3% of its total intensity in the range of rigidities less than 2.2 BV during the era of these observations. The corresponding value of kinetic energy for a proton is $1.46 \times 10^9$ eV. It has been pointed out /Lin and Van Allen, 1963/ that the vertical cut-off rigidity at high latitudes ($L \sim 5.1$) during geomagnetically quiet times (U, the measure for the ring current field, being about 50 gammas) was about 0.24 BV in contrast to 0.56 BV, which is the mean of 0.53 and 0.60, the values for the Northern and Southern Hemispheres as estimated by Quenby and Wenk. An attempt to explain this reduction has been made in terms of the combined effect of the boundary of the magnetosphere ( $\sim$ 8-10 earth radii) and a ring current within the magnetosphere /Akasofu, Lin, and Van Allen, 1963/. This effect extends to higher energies but is probably negligible at rigidities of 2.2 BV.

The apparent integral rigidity-number spectrum of the absolute omnidirectional intensity $J_o$ is

$$J_o\ ( > R) = 4.3\ R^{-0.83 \pm 0.02}\ (cm^2\ sec)^{-1} \tag{1}$$

for $3 < R < 12$ BV and

$$J_o = 2.0\ (cm^2\ sec)^{-1} \tag{2}$$

for $R < 1.7$ BV. In the above R is the Quenby-Wenk vertical cut-off rigidity in BV and $J_o$ is in particles $(cm^2\ sec)^{-1}$.

Results (1) and (2) may be compared with the earlier, cruder results of Van Allen and Singer [1950] in the era 1947-1950.

It is well known that the total intensity $J_o$ of charged particles at points above the atmosphere but below the radiation belts is comprised of three components of comparable magnitude: viz., $J_p$, due to the primary galactic cosmic radiation; $J_{AS}$, due to upward moving, or splash, albedo from reactions in the atmosphere; and $J_{AR}$, due to downward moving, or re-entrant, albedo from reactions in the atmosphere in the opposite hemisphere [Meredith, Van Allen, and Gottlieb, 1955]. Comparison of the present results with the definitive work on the primary spectrum by McDonald and Webber [1962] shows that the albedo contributions are relatively more important at lower latitudes, as might be expected due to the higher average energy of the primaries arriving there. Thus equation (1) above should be regarded as only an empirical interpolation formula and not as the spectral distribution of the primary radiation (or of the albedo components).

An estimate of the contribution of albedo to our value $J_o = 2.0$ particles $(cm^2\ sec)^{-1}$ at high latitudes can be obtained as follows:

$$J_o = J_P + J_{AS} + J_{AR} \; . \tag{3}$$

At high latitudes where the geomagnetic cut-off is low and at an altitude of 1000 km about 70% of $4\pi$ steradians is accessible to an omnidirectional detector. Hence

$$J_P = 0.7\, J_{IP} \tag{4}$$

where $J_{IP}$ is the omnidirectional intensity of galactic cosmic rays in interplanetary space remote from the earth. Van Allen and Frank [1959] found $J_{IP} = 1.8$ particles $(cm^2\ sec)^{-1}$ in March 1959. Thus

$$J_P = 1.26 \text{ particles } (cm^2\ sec)^{-1} \tag{5}$$

and

$$J_{AS} + J_{AR} = 0.74 \text{ particles } (cm^2\ sec)^{-1} = 0.59\ J_P . \tag{6}$$

Figure 6 gives contours for several selected values of the vertical cut-off rigidity computed by Quenby and Wenk and contours for several selected values of the magnetic shell parameter L. There are regions where the two curves run parallel, showing a single valued relationship between the two quantities. This situation is present to a considerable degree in the regions within which our data are registered.

The cosmic ray equator given in the same diagram is the Quenby-Wenk locus of maximum rigidity. It can be seen that the observational minima of cosmic ray intensity fit it rather well. It should be recalled that a similar cosmic ray equator obtained from the computations of Quenby and Webber agrees equally well with the cosmic ray minima. But Pomerantz and Agarwal [1962] have pointed out from plots of intensity versus rigidity, for both the Quenby and Webber and Quenby and Wenk cases, that the latter shows less scatter and hence is an improvement over the former.

It is of interest to investigate the time variation of the observed counting rates during the period of study. The monthly mean counting rates centered on L values 1.15 to 1.95 in steps of 0.1 are shown in Figure 7. The limited amount of data available for the higher L values prevents us from obtaining satisfactory monthly means. We have therefore divided all of the data for $L > 3.0$ into four groups, having equal statistical weight. The mean counting rates for the four periods are plotted in Figure 7 and are also given below.

| Group | Period | Counts $(sec)^{-1}$ |
|---|---|---|
| I | Oct. 13, 1959 to Jan. 6, 1960 | $14.06 \pm 0.45$ |
| II | Jan. 7, 1960 to Mar. 29, 1960 | 14.44 |
| III | Mar. 30, 1960 to Aug. 9, 1960 | 14.21 |
| IV | Aug. 10, 1960 to Feb. 17, 1961 | 14.71 |

Each group consists of about seventy points. Data obtained during Forbush decreases and solar proton events have been excluded. Hence the counting rates provide a good measure of the sum of the intensities of primary galactic cosmic rays and of their charged particle albedo from the atmosphere.

The data up to $L = 2.0$ probably do not reveal any systematic long term change over the whole period on a one standard deviation (S.D.) basis, and certainly not on a 2 S.D. basis.

For $L > 3.0$, the mean counting rate for the entire period is $14.35 \pm 0.22$ counts $(sec)^{-1}$ and no one of the four individual values differs from the mean by as much as one standard deviation. The ratio of the final value to the initial value is $1.046 \pm 0.045$. Hence there is a barely significant increase in counting rate during the 16 month period of observation. The monthly mean counting rate of the Ottawa, Canada neutron monitor increased by 2.4% from October 1959 to December 1960, whereas a total change of this rate of ~ 23% has been reported for a full solar cycle.

22

## SUMMARY OF RESULTS

Using a shielded Geiger tube in the Explorer VII satellite there has been conducted a comprehensive geographic survey of the intensity of charged particles in the latitude range $\pm$ 50.5°, in the altitude range 550 to 1100 km, and over the sixteen month time period October 13, 1959 to February 17, 1961. It has been found possible to identify and eliminate contributions by geomagnetically trapped particles and thus to obtain the absolute intensity of primary galactic cosmic rays and their charged particle secondaries (albedo) produced in the atmosphere. Specific results are as follows:

(a) The counting rate data from both Northern and Southern Hemispheres and over a considerable range of longitudes are represented in a simple and coherent manner as a function of a single parameter, the McIlwain magnetic shell parameter L.

(b) The counting rate increases monotonically with increasing L and has an accurately constant value for $L > 2.9$.

(c) The high latitude knee of the counting rate vs L curve occurs at $L = 2.6$ (corresponding to the invariant latitude 52°) and is indiscernibly different in the Northern and Southern Hemispheres.

(d) The absolute omnidirectional intensity is $0.56\ (\mathrm{cm}^2\ \mathrm{sec})^{-1}$ at the equator and $2.0\ (\mathrm{cm}^2\ \mathrm{sec})^{-1}$ at high latitudes, the ratio being 3.6.

(e) At high latitudes, the intensity increases by the factor $1.046 \pm 0.045$ during the sixteen month period.

(f) In terms of the Quenby-Wenk vertical cut-off rigidity R in BV, the total omnidirectional intensity

$J_o\ (> R) = 4.3\ R^{-0.83 \pm 0.02}\ (\mathrm{cm}^2\ \mathrm{sec})^{-1}$ for $3 < R < 12$ BV

and $J_o = 2.0\ (\mathrm{cm}^2\ \mathrm{sec})^{-1}$ for $R < 1.7$ BV.

ACKNOWLEDGEMENTS

Our thanks are due to Miss Dorothy Weishaar and Mr. V. Seetharamiah for helping reduce the data.

The research for this paper was supported in part by the National Aeronautics and Space Administration Grant NsG-233-62 and by the Office of Naval Research Contract N9onr-93803.

The experimental equipment was developed and built by George H. Ludwig and William A. Whelpley under an I.G.Y. grant of the National Science Foundation.

REFERENCES

Akasofu, S.-I., W. C. Lin, and J. A. Van Allen, "The Entry of Non-Relativistic Solar Protons into the Geomagnetic Field" (to be published).

Chapman, S., "Geomagnetic Nomenclature", J. Geophys. Research 68, 1174 (1963).

Compton, A. H., "Geographic Study of Cosmic Rays", Phys. Rev. 43, 387-403 (1933).

Compton, A. H., and R. Turner, "Cosmic Rays on the Pacific Ocean", Phys. Rev. 52, 799-814 (1937).

Finch, H. P., and B. R. Leaton, "The Earth's Main Magnetic Field--Epoch 1955.0", Monthly Notices Roy. Astron. Soc., Geophys. Suppl. 7, 314-316 (1957).

Forbush, S. E., G. Pizzella, and D. Venkatesan, "The Morphology and Temporal Variations of the Van Allen Radiation Belt, October 1959 to December 1960", J. Geophys. Research 67, 3651-3668 (1962).

Forbush, S. E., D. Venkatesan, and C. E. McIlwain, "Intensity Variations in Outer Van Allen Radiation Belt", J. Geophys. Research 66, 2275-2288 (1961).

Frank, L. A., and J. A. Van Allen, Private Communication (1963).

Garmire, G. P., "An Investigation of the Intensity Distribution and Time Variations of Geomagnetically Trapped Radiation", MIT Dissertation September 1962 (unpublished).

REFERENCES (continued)

Hubach, R. A., "Observations of the Cosmic-Ray Equator in the Pacific Ocean Area", J. Geophys. Research 66, 321-322 (1961).

Katz, L., P. Meyer, and J. A. Simpson, "Further Experiments Concerning the Geomagnetic Field Effective for Cosmic Rays", Nuovo Cimento, Supp. 8, 277-282 (1958).

Lin, W. C., and J. A. Van Allen, "Observation of Solar Cosmic Rays from October 13, 1959 to February 17, 1961 with Explorer VII" (to be published, 1963).

Ludwig, G. H., and W. A. Shelpley, "Corpuscular Radiation Experiment of Satellite 1959 Explorer VII", J. Geophys. Research 65, 1119-1124 (1960).

McDonald, F. B., and W. R. Webber, "A Study of the Rigidity and Charge Dependence of Primary Cosmic Ray Temporal Variations", Proceedings of the International Conference on Cosmic Rays and the Earth Storm, Kyoto, 4-15 September 1961, Vol. II, pp. 428-435 (1962).

McIlwain, C. E., "Coordinates for Mapping the Distribution of Magnetically Trapped Particles", J. Geophys. Research 66, 3681-3692 (1961); Private Communication (1962).

Meredith, L. H., J. A. Van Allen, and M. B. Gottlieb, "Cosmic-Ray Intensity Above the Atmosphere at High Latitudes", Phys. Rev. 99, 198-209 (1955).

Millikan, R. A., "New Techniques in Cosmic-Ray Measurements", Phys. Rev. 43, 661-669 (1933).

REFERENCES (continued)

Millikan, R. A., and H. V. Neher, "World Survey of Sea-Level Cosmic-Ray Intensities", Phys. Rev. 50, 15-24 (1936).

Neher, H. V., "Cosmic Ray Knee in 1958", J. Geophys. Research 66, 4007-4012 (1961).

Pizzella, G., C. E. McIlwain, and J. A. Van Allen, "Time Variations of Intensity in the Earth's Inner Radiation Zone, October 1959 through December 1960", J. Geophys. Research 67, 1235-1253 (1962). See also J. Geophys. Research 67, 4886-4887 (1962), and ibid., 4888-4889 (1962).

Pomerantz, M. A., and S. P. Agarwal, "Spatial Distribution of Cosmic Ray Intensity and Geomagnetic Theory", Phil. Mag. 7, 1503-1512 (1962).

Pomerantz, M. A., A. E. Sandstrom, V. R. Potnis, and D. C. Rose, "Solar Disturbances and the Cosmic Ray Equator", Tellus 12, 231-235 (1960).

Pomerantz, M. A., A. E. Sandstrom, and D. C. Rose, "Shipboard Neutron Monitor Determination of Cosmic-Ray Equator", Nuovo Cimento, Supp. 8, 257-262 (1958).

Quenby, J. J., and W. R. Webber, "Cosmic Ray Cut-Off Rigidities and the Earth's Magnetic Field", Phil. Mag. 4, 90-113 (1959).

Quenby, J. J., and J. Wenk, "Cosmic Ray Threshold Rigidities and the Earth's Magnetic Field", Phil. Mag. 7, 1457-1486 (1962).

REFERENCES (continued)

Ray, E. C., "On the Motion of Charged Particles in the Geomagnetic Field", Goddard Space Flight Center Report X-611-63-43 (1963); also Annals of Physics, in press.

Ray, E. C., and H. H. Sauer, "On Cosmic Ray Cut-Offs", State University of Iowa Research Report 63-8, 19 pp. (March 1963); also Annals of Physics, in press.

Rose, D. C., K. B. Fenton, J. Katzman, and J. A. Simpson, "Latitude Effect of the Cosmic Ray Nucleon and Meson Components at Sea Level from the Arctic to the Antarctic", Canad. J. Phys. 34, 968-984 (1956).

Rothwell, P., and J. Quenby, "Cosmic Rays in the Earth's Magnetic Field", Nuovo Cimento, Supp. 8, 249-256 (1958).

Sauer, H. H., "A New Method of Computing Cosmic-Ray Cutoff Rigidity for Several Geomagnetic Field Models", J. Geophys. Research 68, 957-971 (1963).

Sekido, Y., Y. Asano, and T. Masuda, Sci. Papers Inst. Phys. Research 40, 439 (1943) (see P. Rothwell and J. J. Quenby, 1958).

Simpson, J. A., "Neutrons Produced in the Atmosphere by the Cosmic Radiations", Phys. Rev. 83, 1175-1188 (1951).

Simpson, J. A., K. B. Fenton, J. Katzman, and D. C. Rose, "Effective Geomagnetic Equator for Cosmic Radiation", Phys. Rev. 102, 1648-1653 (1956).

REFERENCES (continued)

Storey, J. R., "Cosmic-Ray Latitude Survey Along 145° East Longitude Using an Airborne Neutron Monitor", Phys. Rev. 113, 297-301 (1959).

Van Allen, J. A., and L. J. Cahill, "A Latitude Survey of Cosmic Radiation", I.G.Y. Rocket Report Series No. 1, National Academy of Sciences - National Research Council, Washington, D. C., pp. 208-210 (30 July 1958).

Van Allen, J. A., and L. A. Frank, "Radiation Measurements to 658,300 Km with Pioneer IV", Nature (London) 184, 219-224 (1959).

Van Allen, J. A., and W. C. Lin, "Outer Radiation Belt and Solar Proton Observations with Explorer VII During March-April 1960", J. Geophys. Research 65, 2998-3003 (1960).

Van Allen, J. A., and S. F. Singer, "On The Primary Cosmic Ray Spectrum", Phys. Rev. 78, 819 (1950); ibid. 80, 116 (1950).

Yoshida, S., G. H. Ludwig, and J. A. Van Allen, "Distribution of Trapped Radiation in the Geomagnetic Field", J. Geophys. Research 65, 807-813 (1960).

## FIGURE CAPTIONS

Figure 1. Several selected contours of constant L at 1000 km altitude computed using McIlwain's program for B and L (private communication, 1962), and the approximate regions over which the Explorer VII data were registered (shown as shaded regions). L is measured in earth radii. The coordinates of the graph are geographic longitude and latitude.

Figure 2. Observed counting rates registered over Woomera, Australia, as a function of L, the magnetic shell parameter. The statistical standard deviation of each plotted point is 13% for L $\lesssim$ 3.0 and 9% for L > 3.0.

Figure 3. Observed counting rates registered in the Northern Hemisphere, other details as in Figure 2.

Figure 4. Dependence of average counting rates on L, for Northern and Southern Hemispheres (derived from Figures 2 and 3). (See text.)

Figure 5. Relation between cut-off rigidity R and magnetic shell parameter L (reproduced from paper by Lin and Van Allen, 1963).

Figure 6. Solid Curves--Contours of constant L in earth radii.

Dashed Curves--Contours of constant vertical cut-off rigidity in BV [Quenby and Wenk, 1962].

Dot-Dash Curve--Locus of points of maximum cut-off rigidity (cosmic ray equator).

Dotted Curve--Locus of points of minimum L.

## FIGURE CAPTIONS (continued)

Figure 6. (cont.) Observed minima of cosmic ray intensities

| | |
|---|---|
| ■ | (Compton et al., 1937) |
| + | (Rose et al., 1956) |
| □ | (Simpson, 1951) |
| o | (Pomerantz et al., 1958) |
| ( ) | (Pomerantz et al., 1960) |
| x | (Sekido et al., 1943) |
| • | (Rothwell et al., 1958) |
| ▲ | (Katz et al., 1958) |
| ▽ | (Storey, 1959) |
| ◇ | (Hubach, 1961) |

Figure 7. Counting rates in various ranges of L versus time.

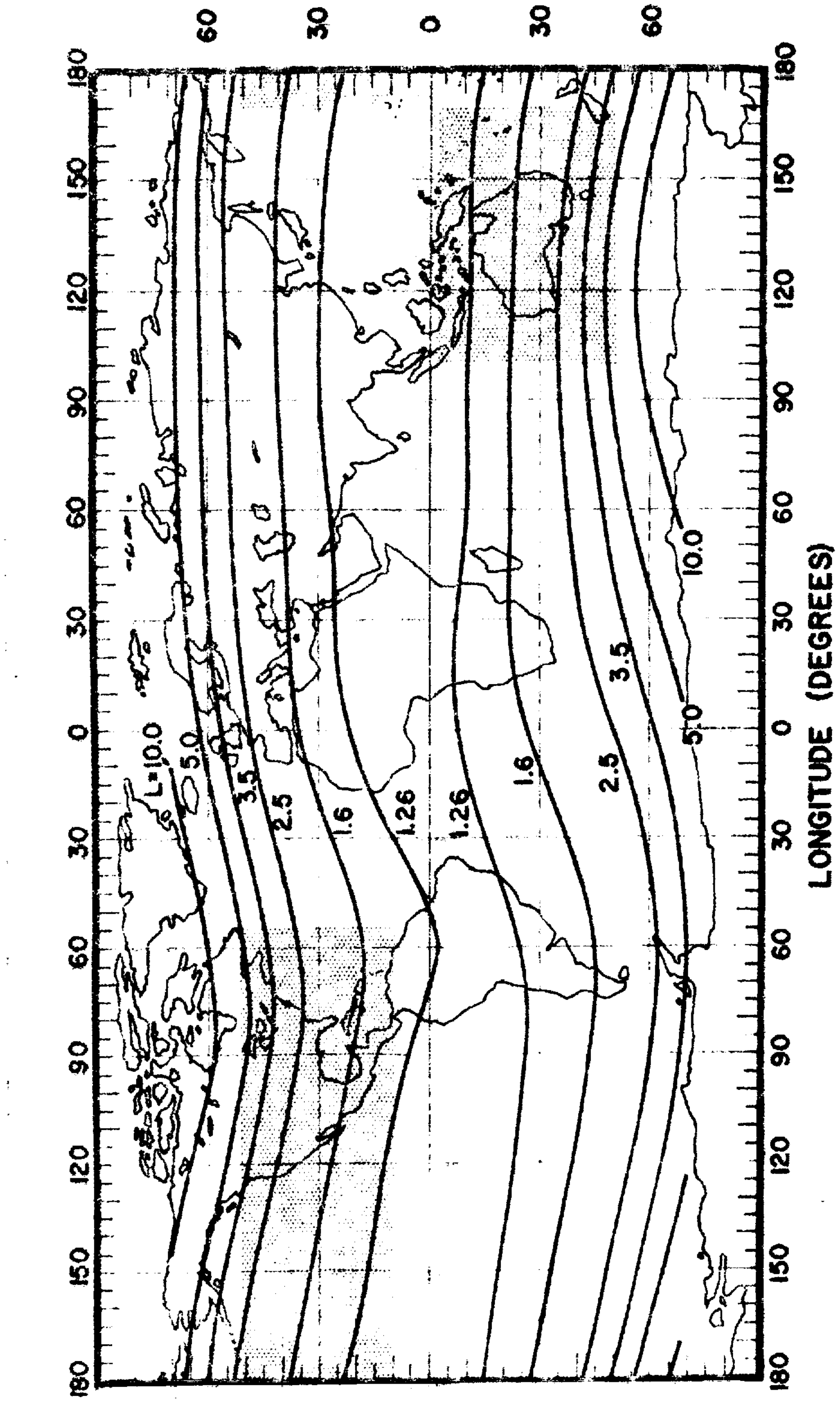



Figure 1

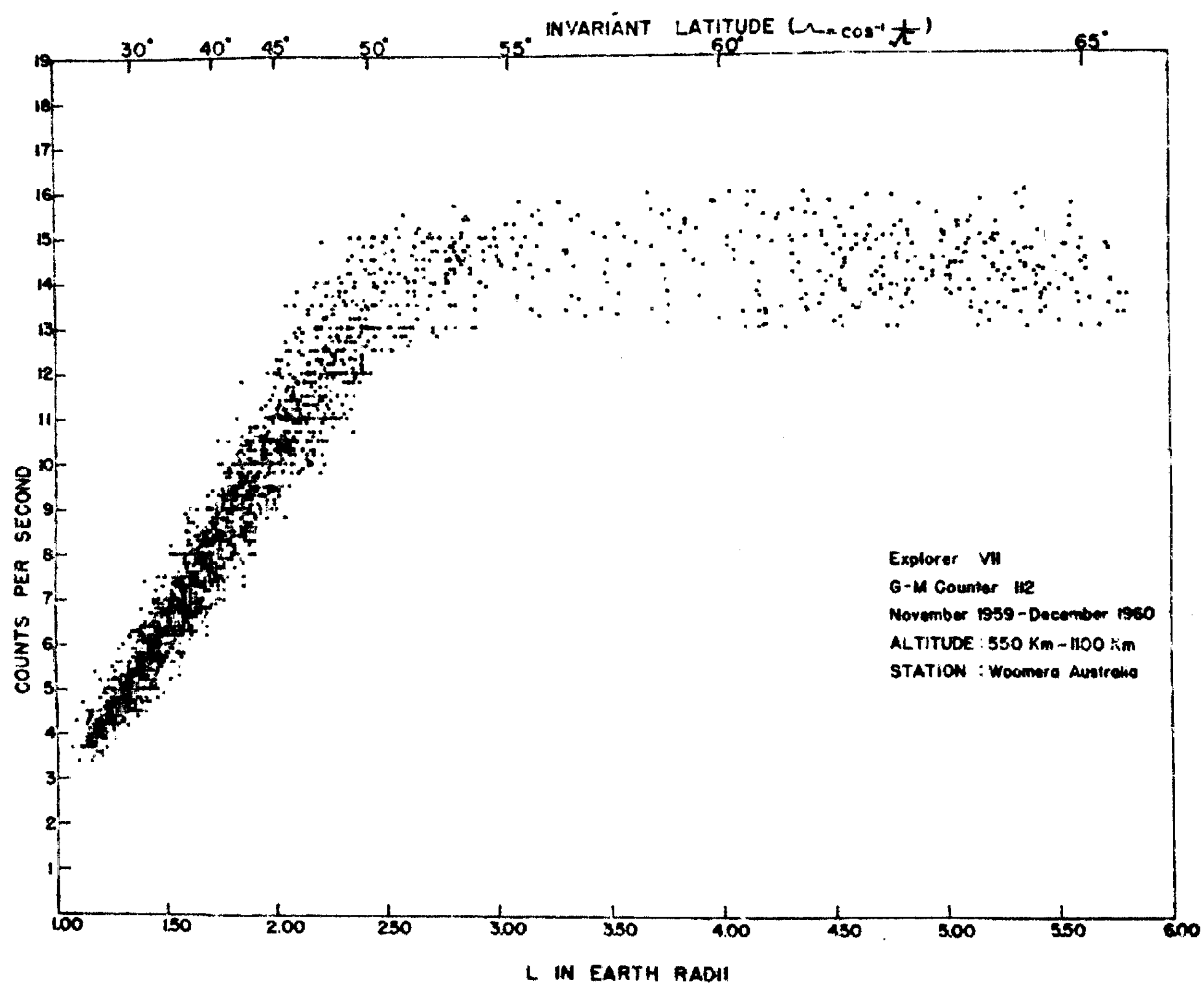

INVARIANT LATITUDE
30° 40° 45° 50° 55° 60° 65°
COUNTS PER SECOND
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00 5.50 6.00
L IN EARTH RADII
Explorer VII
G-M Counter 112
November 1959 - December 1960
ALTITUDE : 550 Km - 1100 Km
STATION : Woomera Australia

Figure 2

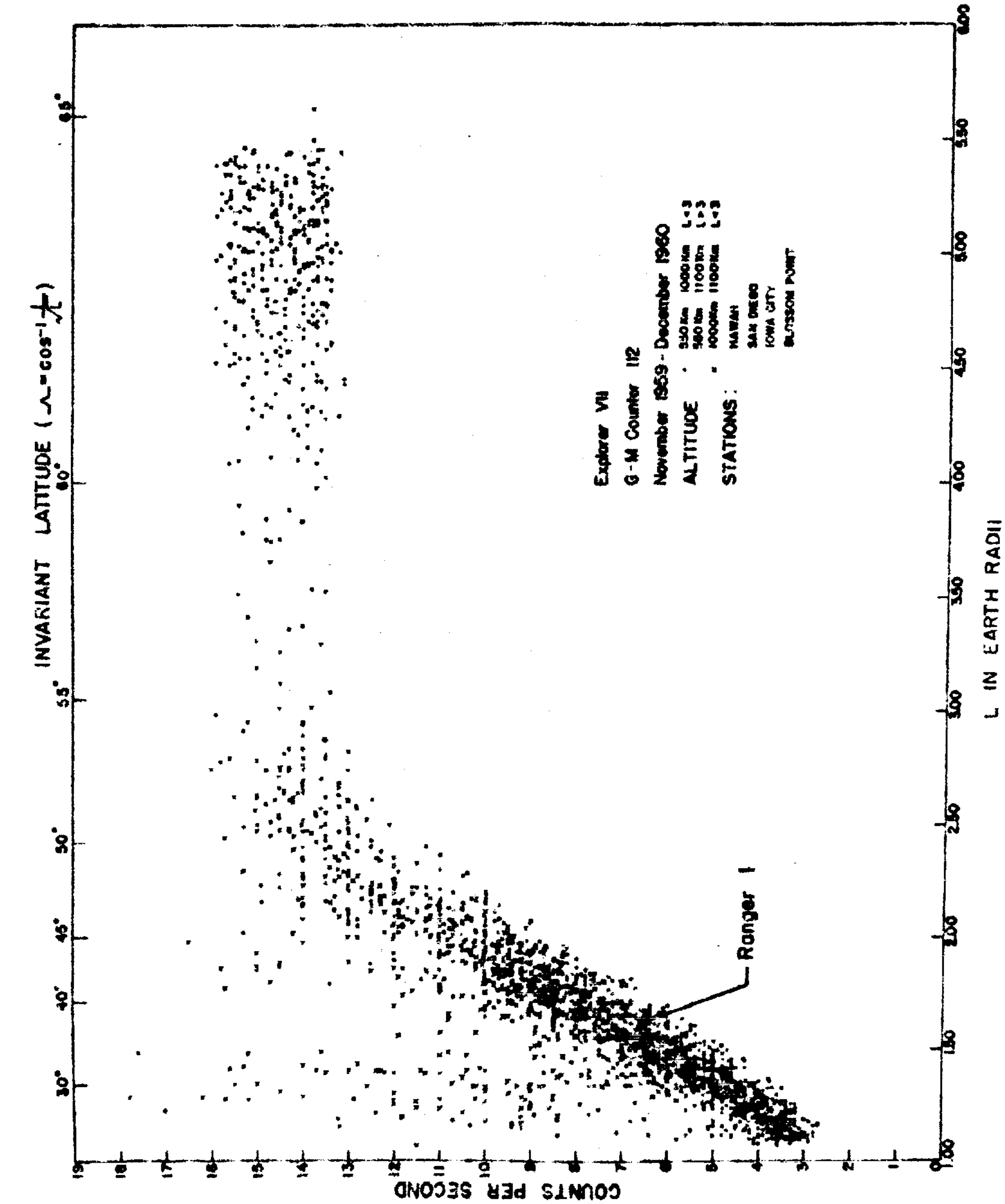
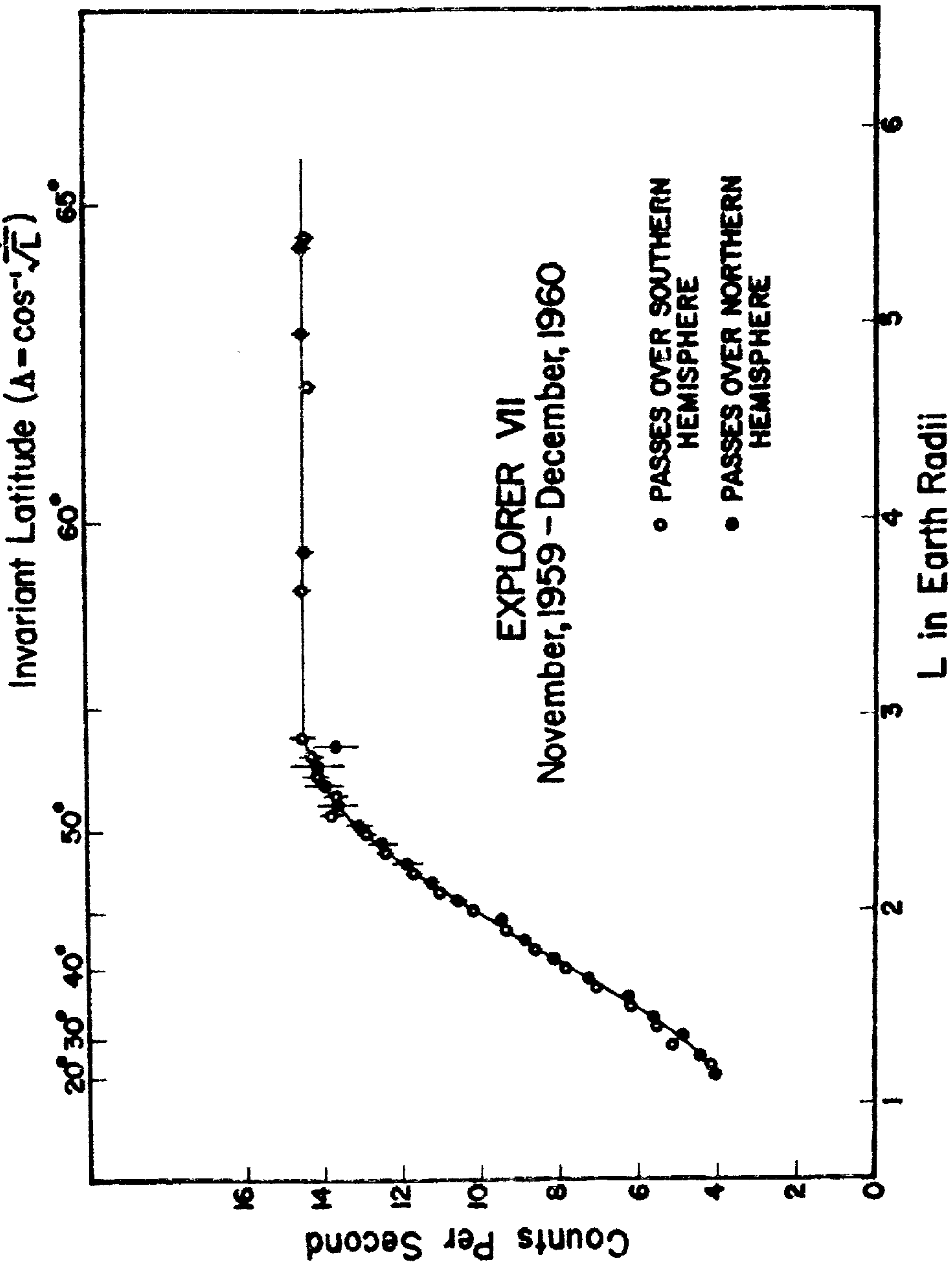

INVARIANT LATITUDE
COUNTS PER SECOND
L IN EARTH RADII
Explorer VII
G-M Counter 112
November 1959 - December 1960
ALTITUDE
STATIONS :
HAWAII
SAN DIEGO
IOWA CITY
BLOSSOM POINT
Ranger I

Figure 3



Invariant Latitude ($\Lambda = \cos^{-1}\frac{1}{\sqrt{L}}$)
20° 30° 40° 50° 60° 65°
EXPLORER VII
November, 1959 - December, 1960
○ PASSES OVER SOUTHERN HEMISPHERE
● PASSES OVER NORTHERN HEMISPHERE
Counts Per Second
0 2 4 6 8 10 12 14 16
1 2 3 4 5 6
L in Earth Radii


Figure 4

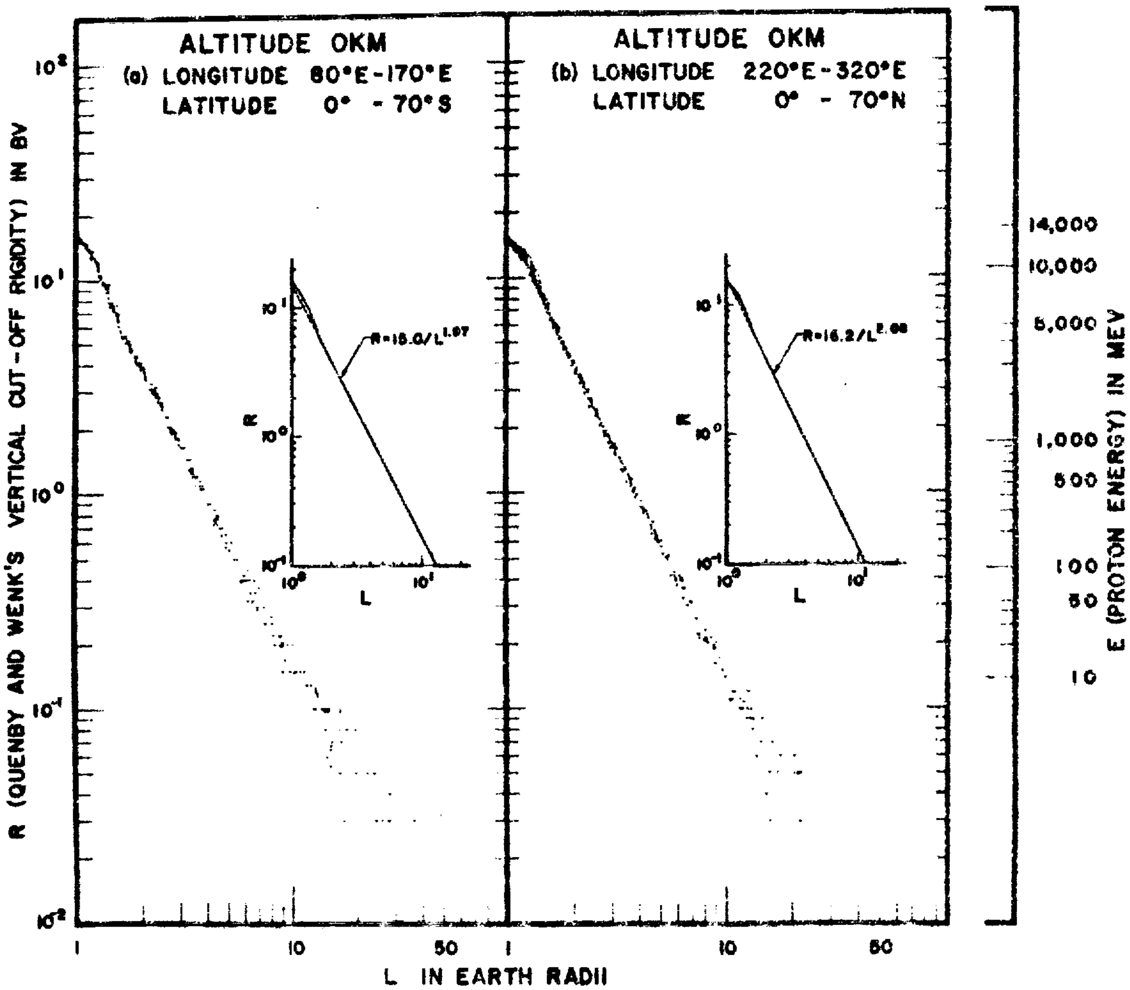

ALTITUDE OKM
(a) LONGITUDE 80°E-170°E
LATITUDE 0° - 70°S
ALTITUDE OKM
(b) LONGITUDE 220°E-320°E
LATITUDE 0° - 70°N
R (QUENBY AND WENK'S VERTICAL CUT-OFF RIGIDITY) IN BV
E (PROTON ENERGY) IN MEV
L IN EARTH RADII
L
R
R=15.0/L^1.97
R=16.2/L^2.08
14,000
10,000
5,000
1,000
500
100
50
10

Figure 5

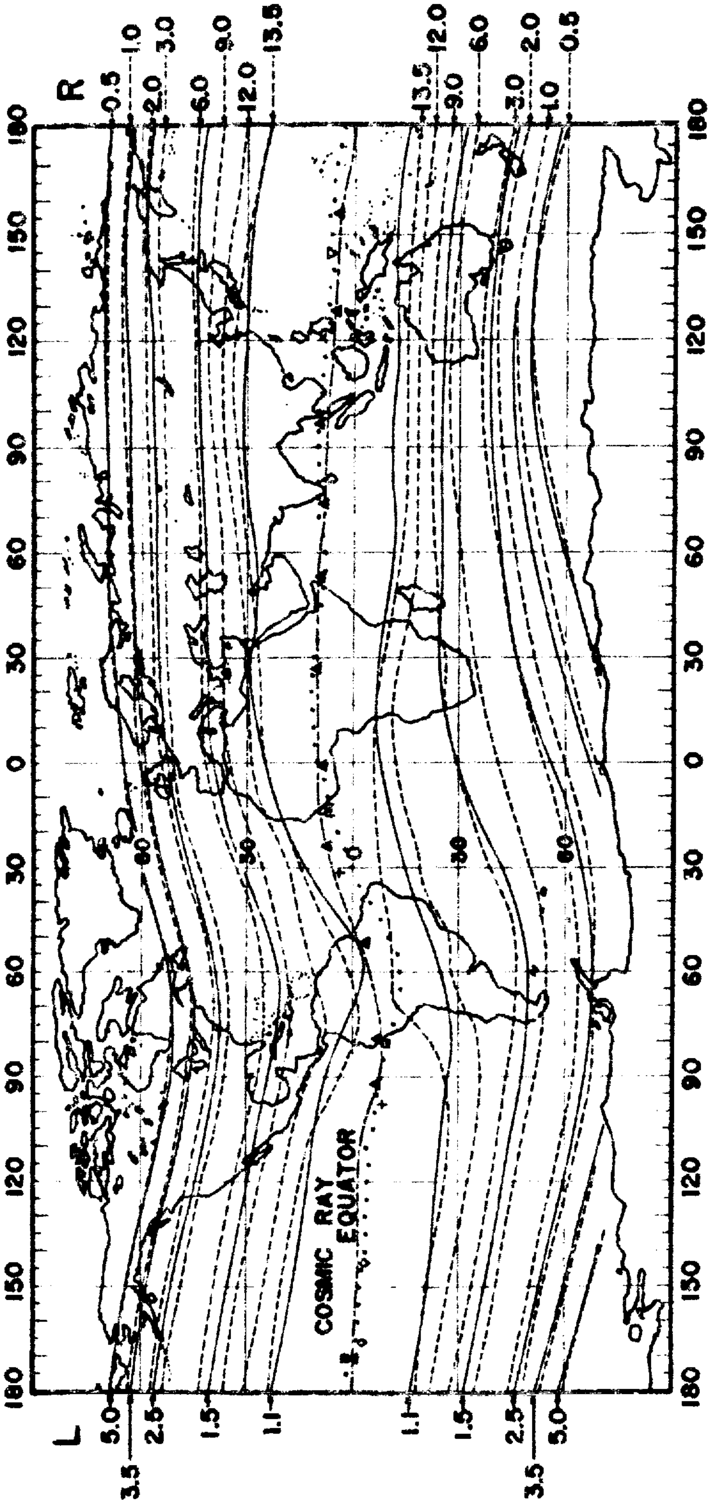

R
0.5
1.0
2.0
3.0
6.0
9.0
12.0
13.5
L
5.0
3.5
2.5
1.5
1.1
COSMIC RAY EQUATOR
180
150
120
90
60
30
0

Figure 6

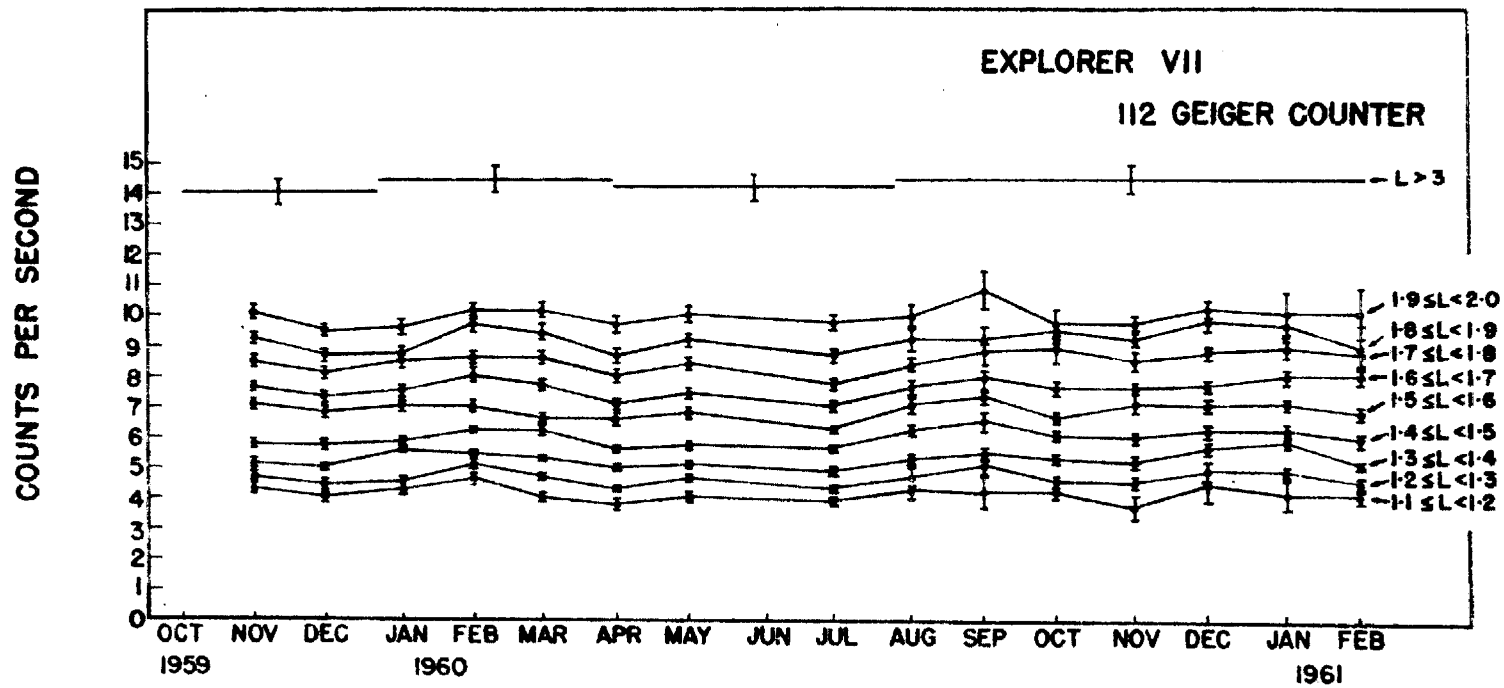

EXPLORER VII
112 GEIGER COUNTER
COUNTS PER SECOND
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
OCT 1959
NOV
DEC
JAN 1960
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
JAN 1961
FEB
L > 3
1·9 ≤ L < 2·0
1·8 ≤ L < 1·9
1·7 ≤ L < 1·8
1·6 ≤ L < 1·7
1·5 ≤ L < 1·6
1·4 ≤ L < 1·5
1·3 ≤ L < 1·4
1·2 ≤ L < 1·3
1·1 ≤ L < 1·2

Figure 7